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An empirical calibration of the mixing-length parameter α [1]

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ABSTRACT

We present an empirical calibration of the Mixing-Length free parameter α based on a homogeneous Infrared database of 28 Galactic globular clusters spanning a wide metallicity range (-2.15<[Fe/H]<-0.2). Empirical estimates of the red giant effective temperatures have been obtained from infrared colors. Suitable relations linking these temperatures to the cluster metallicity have been obtained and compared to theoretical predictions. An appropriate set of models for the Sun and Population II giants have been computed by using both the standard solar metallicity $[Z/X]_{\odot} = 0.0275$ and the most recently proposed value $[Z/X]_{\odot}$ =0.0177. We find that when the standard solar metallicity is adopted, a unique value of α=2.17 can be used to reproduce both the solar radius and the population II red giant temperature. Conversely, when the new solar metallicity is adopted, two different values of α are required: $\alpha = 1.86$ to fit the solar radius and $\alpha \approx 2.0$ to fit the red giant temperatures. However, it must be noted that, regardless the adopted solar reference, the α parameter does not show any significant dependence on metallicity.

Subject headings: Globular clusters: general; stars: evolution – stars: Population II

[1]Based on observations collected at the European Southern Observatory (ESO), La Silla, Chile. Also based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Fundacion Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

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1. Introduction

Stellar evolutionary models are common ingredients in a variety of studies addressing fundamental cosmological and astrophysical problems, such as ages, formation processes, and evolution of galaxies. However, stellar sequences need to be properly checked and calibrated before using them to derive properties of complex stellar systems. As extensively reviewed by Renzini & Fusi Pecci (1988), beside model testing, one should also take into account as a separated issue the calibration of those quantities that theoretical models are forced to parameterize because of the insufficient understanding of the physical process. In this contest, the lack of a rigorous theory of convection remains one of the major deficiencies in the calculations of stellar evolutionary sequences. Despite many efforts to replace the mixing–length (ML) theory of convection by less crude approximations (see Canuto & Mazzitelli 1991; Spruit 1997; Ludwig, Freytag & Steffen 1999), the classical formulation of Bohm–Vitense (1958) continues to be universally used. The ML algorithm requires the presence of the free parameter $\alpha = l/H_p$, which represents the ratio between the mean free path of a convective element (l) and the pressure scale height (H_p): the variations of this parameter strongly affects the structure of the outer envelope (i.e. radius and temperature). In fact, this parameter determines the efficiency of energy transport by convection in the outermost layer of a star: for a given stellar luminosity, it fixes the radius of the star, hence its temperature and colors. Evolutionary tracks must then be calibrated by comparison with stellar radii and/or temperatures derived from observations. The most obvious ML calibrator is the Sun. The ML parameter can be fixed by constraining theoretical solar models (i.e. with solar mass, age and chemical composition) to reproduce the solar radius (see e.g. Mazzitelli 1979; Sweigart 1983; VandenBerg 1983). The solar calibrations suggest that the parameter α should range from 1.5 to 2, when the classical ML algorithm is used (Cox & Giuli 1968). Observational evidences have shown that similar values can account for *(i)* the lower Main–Sequence (MS) slope of young open clusters (VandenBerg & Bridges 1984), *(ii)* the positions in the Color-Magnitude Diagram (CMD) of the local Population II sub-dwarfs (Buonanno et al. 1988), *(iii)* the properties of well–observed binaries whose components are in widely separated evolutionary phases (VandenBerg & Hrivnak 1985), and *(iv)* the effective temperature of Red Giant Branch (RGB) stars (Straniero & Chieffi 1991; Chieffi, Straniero & Salaris 1995; VandenBerg et al. 2000; Alonso et al. 1999, 2000). However, although similar α values have been derived by using different ML–calibrators, there is no theoretical justification that the same value of α should apply to any star.

In addition, Chieffi, Straniero & Salaris (1995) emphasized that in the case of low-mass stellar models the derived stellar radii depend on the opacity which significantly contributes in determining the temperature gradient in their turbulent external layers. Hence, stellar models, based on different opacity tables, could require different values of α.

An homogeneous dataset of stellar temperatures at different metallicities to properly calibrate the ML parameter is urgently needed before any further attempt to use evolutionary models to derive relevant properties of stellar populations.

In this paper we present an empirical calibration of the α parameter, based on accurate estimates of the RGB effective temperature at fixed luminosity levels for a homogeneous sample of Galactic Globular Clusters (GCs) with different metallicity, observed by our group in the last 10 years (see i.e. Ferraro et al. 2000; Valenti, Ferraro & Origlia 2004a; Valenti et al. 2004; Sollima et al. 2004; Valenti, Origlia & Ferraro 2005). This infrared data-set is the ideal tool to properly calibrate the α parameter for low-mass stellar models and to study its possible dependence on metallicity.

2. The mixing length

One of the main source of uncertainty in stellar models concerns the efficiency of convection. In the external layer of a red giant star, the convective heat transfer may substantially departs from the adiabatic regime, in which any internal excess of heat is efficiently transported outward by the ascending convective bubbles. In the framework of the standard ML theory, the convective efficiency is tuned by changing the α parameter. Large values of α (i.e. larger than 2.5) corresponds to a very efficient convection. In this case, the temperature gradient is close to the minimum allowed value (the adiabatic one) and the predicted red giant temperature are larger. On the contrary, for lower values of the α parameter, the internal heat excess is only partially removed by convection, and the radiative energy transport plays an important role. This is the case of GC RGB stars, where the stellar effective temperature is sensitive to the radiative opacity. For this reason, models computed with the same α value, but larger opacity, produce lower effective temperatures. Hence a proper variation of α may counterbalance a variation of low temperature opacities (Chieffi, Straniero & Salaris 1995).

The α parameter is usually calibrated by forcing stellar models of the Sun to fit the solar radius, which is known with high precision. However, the envelope of a red giant has rather different physical characteristics with respect to the solar envelope. A direct comparison of empirical temperatures of red giant stars with the corresponding model predictions, provides an independent calibration of α and allows us to measure the efficiency of the convective energy transport in very different physical conditions.

3. The empirical database

The homogeneous data-set of fiducial RGB ridge lines presented here is based on high quality J, H and K photometry of 28 Galactic GCs published by our group in the last few years (Ferraro et al. 2000; Valenti et al. 2004; Valenti, Ferraro & Origlia 2004a; Sollima et al. 2004; Valenti, Origlia & Ferraro 2005). The data were obtained at ESO La Silla Observatory (Chile) using IRAC2@ESO/MPI2.2m and SofI@NTT/ESO IR cameras and at the Telescopio Nazionale Galileo with ARNICA in several observing runs. On average, the central ∼20 arcmin^2 of each cluster has been mapped, allowing us to sample a significant fraction of the total cluster light (typically ≈70–90%). For all the programme clusters the same data reduction procedure has been applied (see Valenti, Ferraro & Origlia 2004a, for more details); the instrumental magnitudes have been calibrated into the 2MASS photometric and astrometric system, allowing us to build the largest homogeneous IR database of GCs ever obtained[5].

For all the clusters listed in Table 1, the observations were deep enough to properly sample the entire RGB extension, from the base (typically 2–3 magnitudes below the Horizontal Branch (HB)) up to the RGB-Tip, thus allowing us a complete study of the RGB morphological features and a clear definition of the mean ridge line (see e.g. Fig. 1 and 2 of Valenti, Ferraro & Origlia 2004a; Valenti, Origlia & Ferraro 2005).

The detailed procedure followed to obtain the RGB fiducial ridge lines of the clusters and to transform them into the absolute plane can be found in Ferraro et al. (2000). Since for the aim of this study the homogeneity of the data-set is a crucial issue, we adopt the distance scale established by Ferraro et al. (1999) based on an empirical measurement of the Zero Age HB level in a sample of 61 Galactic GCs. Note that the Ferraro et al. (1999) distance scale has been adopted by Ferraro et al (2000), Valenti, Ferraro & Origlia (2004b) in order to perform a detailed comparison of the observed RGB Bump and Tip luminosity with theoretical expectations, finding an excellent agreement. However it is worth of noticing that the assumption of a different distance scale has a little effect on the derived temperatures. In fact, even a significant difference in the adopted distance moduli of $\pm 0.1 mag$ would produce only a difference of $\pm 30K$ in the derived temperatures.

Reddening values have been taken from Harris (1996) for all the clusters but the most extincted ones towards the Bulge direction, for which a differential method based on the comparison of CMDs and Luminosity Functions (LFs) with those of a reference cluster of similar metallicity, has been applied (see Valenti, Ferraro & Origlia 2004a, for more details).

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[5]The photometric catalogs are available in electronic form at the CDS web site.

In order to use these empirical data-set for the calibration of theoretical models, the mean ridge lines in the $[M_K, (J-K)_0]$ observational plane must be transformed into the M_{Bol}, Log T_e theoretical one. In doing this we adopted the bolometric correction (BC_K) and the temperature scale computed by Montegriffo et al. (1998). These empirical relations have been specifically calibrated on Population II giants in Galactic GCs (see also Alonso et al. 1999). Fig. 1 shows the fiducial RGB ridge lines for the 28 Galactic GCs in our sample in the M_{Bol}, $\log(T_e)$ theoretical plane.

3.1. The metallicity scale

As widely discussed in Ferraro et al. (1999, 2000) the location of the RGB in color (i.e. in temperature) strongly depends on the cluster metal content. Indeed, the effective temperature of a red giant star decreases when the total mass fraction of heavy elements (Z) increases, mainly because of the larger opacity. Actually, electron donors, like Fe and α-elements, provides the free electrons needed to form H^- ions, which are the most important opacity source in the cool red giant envelope. Thus, stars with similar Z, but different distribution of heavy elements, should have similar RGB temperatures, if the total amount of electron donors is similar. This is the case, for example, of scaled solar and alpha-enhanced mixtures with the same Z (Salaris, Chieffi & Straniero 1993) [6]. On the contrary, the He content (Y) and the mass (M), only slightly affect the RGB effective temperature: a similar variation of the effective temperature $\delta LogT_e \approx -0.005$ is indeed obtained for masses increasing from 0.8 to 0.9 $M_\odot$ or for Y increasing from 0.245 to 0.30. Hence, the correct parameterization of the RGB location does require the precise knowledge of the so--called global metallicity, which takes also into account the contribution of the α–elements, in particular the $[Mg + Si + Fe]$ abundance mixture, rather than relying on the [Fe/H] abundance alone (Straniero & Chieffi 1991; Salaris & Cassisi 1996).

In our previous works (Ferraro et al. 2000; Valenti et al. 2004; Valenti, Ferraro & Origlia 2004a; Valenti, Origlia & Ferraro 2005) we have computed the global metallicity [M/H] from the Carretta & Gratton (1997) scale ($[Fe/H]_{CG97}$) by adopting an enhancement factor of the α–element linearly decreasing to zero for metal–rich clusters with $[Fe/H]_{CG97} > -1$. However, there is now a growing number of evidences that this trend is not applicable to the Bulge clusters. In fact, the most recent high resolution spectroscopic observations of both Bulge cluster and field giants (Rich & McWilliam 2000; Carretta et al. 2001; Origlia, Rich & Castro 2002; Origlia & Rich 2004; Zoccali et al. 2004; Origlia, Valenti & Rich 2005;

[6] The difference in effective temperature may be somewhat larger at high metallicity (Kim et al. 2002).

Rich & Origlia 2005; Origlia et al. 2005) suggest an α–enhancement up to solar metallicity. Hence, here we have adopted a constant α–enhancement ([α/Fe]$\sim$0.3 dex) over the entire -2.2<[Fe/H]$_{CG97}$ <-0.1 range of metallicities. For the NGC 6553 and NGC 6528 clusters, which represent the metal–rich extremes of our entire database, we use the updated values inferred from high–resolution IR spectroscopy by Origlia, Rich & Castro (2002); Origlia, Valenti & Rich (2005) (see also Carretta & Gratton 1997; Carretta et al. 2001; Melendez et al. 2003; Zoccali et al. 2004). The adopted metallicity for all the programme clusters are listed in column [3] of Table 1.

4. Results and Discussion

We used the CMD plotted in Fig. 1 to measure the RGB effective temperatures at fixed bolometric magnitudes, namely M_{Bol}=-3, -2, -1, respectively. The derived values are listed in Table 1 together with a formal uncertainty of 50–100 K, and plotted in Fig. 2 as a function of the cluster global metallicity ([M/H]). Well defined quadratic relations best fit the observed data with a very small r.m.s. ($\Delta \log T_e \leq 0.01$). These relations can serve as calibrators for the current and future generations of theoretical models for Population II stars. In the following, we use them to calibrate the α parameter for the stellar evolution code described by Straniero, Chieffi & Limongi (1997, hereafter, SCL97), which adopts the latest input physics and the opacity from OPAL above $logT_{eff}$ = 3.75, and Alexander & Fergusson (1994) for $logT_{eff} < 3.75$.

As a first step, we have used this code to compute a standard solar model and tune the α parameter in order to reproduce the solar radius. In doing this we followed the procedure described in Chieffi, Straniero & Salaris (1995).

An important consideration concerning the adopted solar abundances is worth noticing. The Anders & Grevesse (1989, hereafter AG89) values (giving a total metallicity $(Z/X)_{\odot}$ = 0.0275) have been widely used for years. However, more recently significantly lower abundances have been proposed by Lodders (2003, hereafter, L03) ($(Z/X)_{\odot} = 0.0177$) and by Asplund, Grevesse & Sauval (2005) ($(Z/X)_{\odot}$ = 0.0165), both using C,N,O abundances from 3D model atmospheres (see also Allend Prieto, Lambert & Asplund 2002). By adopting both the AG89 and the L03 solar compositions, we have found that the best SCL97 models to reproduce the solar radius require $\alpha = 2.17$ and $\alpha = 1.86$, respectively.

Then, by using the same code (SCL97) and the same input physics, we have computed a set of RGB models for low-mass Population II stars. Of course, in order to compare the empirical effective temperatures with those predicted by stellar models, we need the absolute

abundance of metals, namely Z. The relation between these two quantities is:

$$[M/H] = log(Z/X) - log(Z/X)_{\odot}.$$

Here $X = 1 - Y - Z$ is the mass fraction of H in the envelope of our star/model. Thus, the absolute amount of heavy elements in a star with known [M/H], substantially depends on the Z/X ratio in the solar photosphere $[(Z/X)_{\odot}]$. Hence, for example, for $[M/H] = -1.5$, one obtains Z/X=0.00056, with the latest solar abundances by L03, or Z/X=0.00087, with the widely adopted AG89 ones.

We have computed a set of RGB models with fixed mass (M=0.8 $M_{\odot}$). Z has been varied from 0.0001 to 0.02. In our analysis, if not explicitly specified, we adopt $Y = 0.245$, a value in agreement with the latest determination of the primordial He abundance (Cassisi, Salaris & Irwin 2003). A $10 - 20\%$ uncertainty in X (or Y) induces a variation of Z that is always smaller than the 1σ error in the $[M/H]$ empirical estimates. The initial heavy elements distribution is scaled solar, using both the AG89 and L03 references.

Fig. 3 reports the results. By using the AG89 solar reference, the measured RGB temperatures are well reproduced by the $\alpha = 2.17$ curve, the same value obtained by best fitting the solar radius. Conversely, by using the L03 solar reference, the α value adopted to reproduce the Sun ($\alpha = 1.86$) systematically underestimates the giant temperatures, while the model with $\alpha = 2.17$ systematically overestimates them. The accurate inspection of Fig.3 suggests that the observational data are best reproduced by a model with an intermediate value of the ML parameter ($\alpha \approx 2$).

Hence, from the comparison of the empirical data with theoretical predictions, we find that by adopting the "old" solar abundances by AG89 both the solar and the Population II Red Giant structure (regardless of the metallicity) can be nicely reproduced with a single value of the ML parameter ($\alpha = 2.17$). Conversely, different values of α for the Sun (1.86) and the giant stars (2.0) are required when the L03 solar abundances are used. Note that the curve with $\alpha = 2.0$ for the L03 solar metallicity is not plotted in Figure 3 since it is nearly coincident with the one obtained with $\alpha = 1.86$ for the AG89 solar reference (solid line in Figure 3).

As already stated in Sect. 1, in principle, there is no theoretical reason that the same value of α should apply to any star, hence, the two results are formally equally possible.

However, there are other issues that should be considered and discussed. For example, it must be noticed that the empirical abundances for the clusters listed in Table 1, have been derived using 1D model atmospheres and 1D solar references like AG89 or subsequent

updates. Conversely, the L03 solar references are partially based on abundances derived from 3D models. Hence, the results using the L03 solar references have to be taken with caution, since only when both a complete set of solar abundances and a re-analysis of the empirical stellar abundances, fully based on 3D model atmospheres (see e.g. Kucinskas et al. 2005) will be available, firm conclusions can be drawn.

A significant discrepancy between theory and observation has been already noticed when the "new" L03 solar abundance have been used to compute standard solar models. Indeed, the predicted depth of the solar convective zone, as obtained by adopting the new CNO abundances from Asplund (2003), is significantly larger than the one derived from the analysis of the helio-seismic data (Bahcall et al. 2003). The bad news is even worst, because an excellent reproduction of the seismic data was previously found by adopting the "old" AG89 solar abundances. Bachall et al. (2005) invokes a significant increase of the solar Ne (about 10^3 times larger) to solve the solar convective zone problem. A recent analysis of X-ray spectra of nearby stars (Darke & Testa 2005) seems to confirm this expectation. Note that such a substantial increase of the solar Ne abundance would also affect the relation between [M/H] and Z and, in turn, the calibration of the ML.

While the issue of the firm determination of the absolute solar abundance will be addressed by future spectroscopic works, the major result presented here is that, regardless of the adopted solar reference, there is not any clear evidence, within the errors, of a significant dependence of the ML parameter from the stellar metallicity (see also Palmieri et al. 2002). This is a somewhat surprising result, since the classical formulation of the ML theory (Bohm-Vitense 1958) is a quite naive approximation of the mean free path of the convettive bubbles based on very simple assumptions. The results showed here suggest that in spite of these crude approximations and the very basic assumptions, the efficiency of the convective energy transport parametrized by α is mainly controlled by the local value of H_p and it does not require any extra dependence from the metallicity of the environment, once an appropriate set of opacity coefficients have taken into account in the calculation of the stellar model.

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Table 1: The cluster sample

Name	$[Fe/H]_{CG97}$	[M/H]	log $T_e^{(M_{Bol}=-3)}$	log $T_e^{(M_{Bol}=-2)}$	log $T_e^{(M_{Bol}=-1)}$	Ref$^{(*)}$
M 92	-2.16	-1.95	3.648±0.008	3.675±0.008	3.695±0.008	V04
M 15	-2.12	-1.91	3.639±0.008	3.667±0.008	3.689±0.008	V04a
M 68	-1.99	-1.81	3.642±0.008	3.667±0.008	3.687±0.008	F00
M 30	-1.91	-1.71	3.656±0.008	3.680±0.008	3.696±0.008	V04a
M 55	-1.61	-1.41	3.636±0.008	3.667±0.008	3.688±0.008	F00
ω Cen	-1.60	-1.39	3.629± 0.008	3.649± 0.008	3.668± 0.008	S04$^{(**)}$
NGC6752	-1.42	-1.21	3.610± 0.011	3.638± 0.011	3.663±0.011	V04a
M 10	-1.41	-1.25	3.635± 0.011	3.661± 0.011	3.683±0.011	V04
M 13	-1.39	-1.18	——	3.617± 0.011	3.646±0.011	V04
M 3	-1.34	-1.16	3.605± 0.011	3.634± 0.011	3.657±0.011	V04
M 4	-1.19	-0.94	——	3.620± 0.011	3.647±0.011	F00
NGC 362	-1.15	-0.99	——	3.613± 0.014	3.638± 0.014	V04a
M 5	-1.11	-0.90	——	3.612± 0.014	3.638± 0.014	V04
NGC 288	-1.07	-0.85	——	3.629± 0.014	3.652± 0.014	V04a
NGC 6638	-0.97	-0.69	3.584± 0.012	3.615± 0.012	3.641± 0.012	V05
M 107	-0.87	-0.67	3.568± 0.012	3.606± 0.012	3.637± 0.012	F00
NGC 6380	-0.87	-0.66	3.573±0.012	3.607±0.012	3.636±0.012	V04a
NGC 6569	-0.79	-0.58	3.574±0.012	3.604±0.012	3.631±0.012	V05
NGC 6539	-0.71	-0.50	3.556±0.012	3.593±0.012	3.623±0.012	O05
NGC 6342	-0.71	-0.50	3.556±0.012	3.591±0.012	3.619±0.012	V04a
47 tuc	-0.70	-0.59	3.556±0.012	3.597±0.012	3.627±0.012	F00
NGC 6637	-0.68	-0.55	3.563±0.012	3.597±0.012	3.627±0.012	V05
NGC 6304	-0.68	-0.47	3.564±0.012	3.596±0.012	3.624±0.012	V05
NGC 6441	-0.68	-0.47	3.571±0.012	3.606±0.012	3.634±0.012	V04a
NGC 6624	-0.63	-0.42	3.560±0.012	3.596±0.012	3.625±0.012	V04a
NGC 6440	-0.49	-0.28	3.555±0.012	3.592±0.012	3.621±0.012	V04a
NGC 6553	-0.30$^{(***)}$	-0.09	3.549±0.012	3.587±0.012	3.619±0.012	F00
NGC 6528	-0.17$^{(***)}$	+0.04	3.533±0.012	3.567±0.012	3.599±0.012	F00

Notes:
$^{(*)}$ F00: Ferraro et al. (2000); V04: Valenti et al. (2004); V04a: Valenti, Ferraro & Origlia (2004a); S04: Sollima et al. (2004); V05: Valenti, Origlia & Ferraro (2005); O05: Origlia et al. (2005)
$^{(**)}$ The listed values refer to the metal poor dominant population of ω Centauri (see S04 for additional details).
$^{(***)}$ From Origlia, Rich & Castro (2002); Origlia, Valenti & Rich (2005).

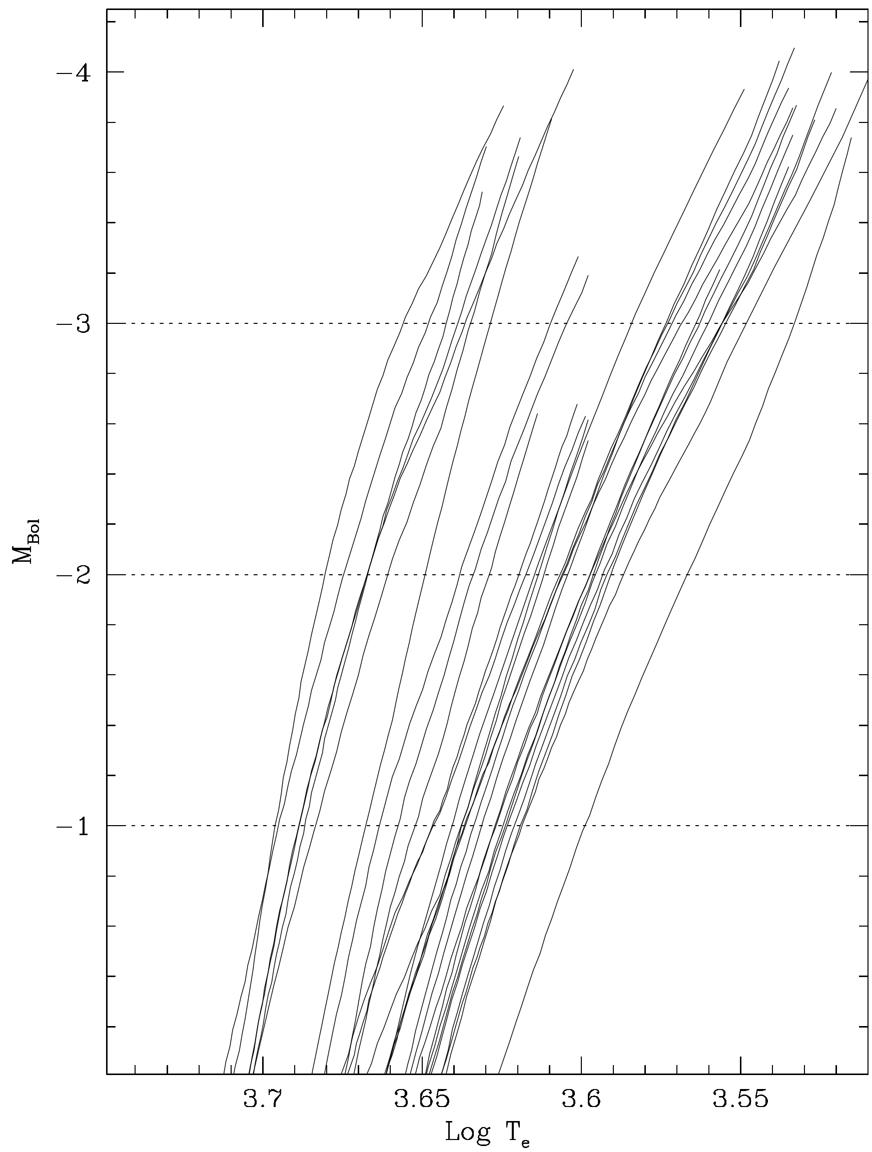

Fig. 1.— RGB fiducial ridge lines in the [M_{Bol}, log(T_e)] theoretical plane for the 28 GGCs in our sample.

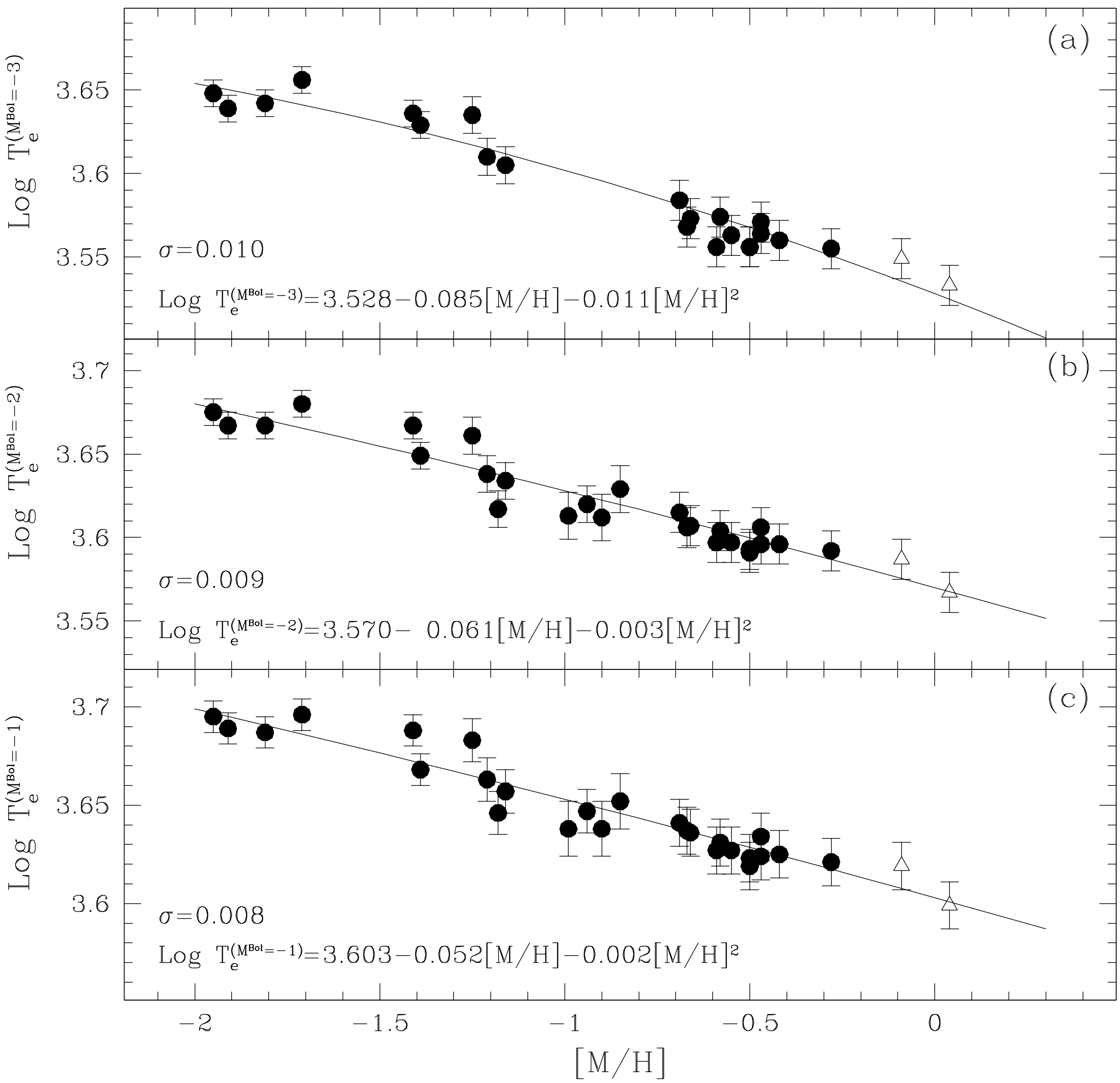

Fig. 2.— Log T_e at M_{Bol}=-3,-2,-1 (panel a, b, c, respectively) as a function of the global metallicity scale for the 28 GCs in our sample. The solid lines are the best fit to the data. The empty triangles refer to NGC 6553 and NGC 6528 with the most recent metallicity estimates by Origlia, Rich & Castro (2002); Origlia, Valenti & Rich (2005) respectively.

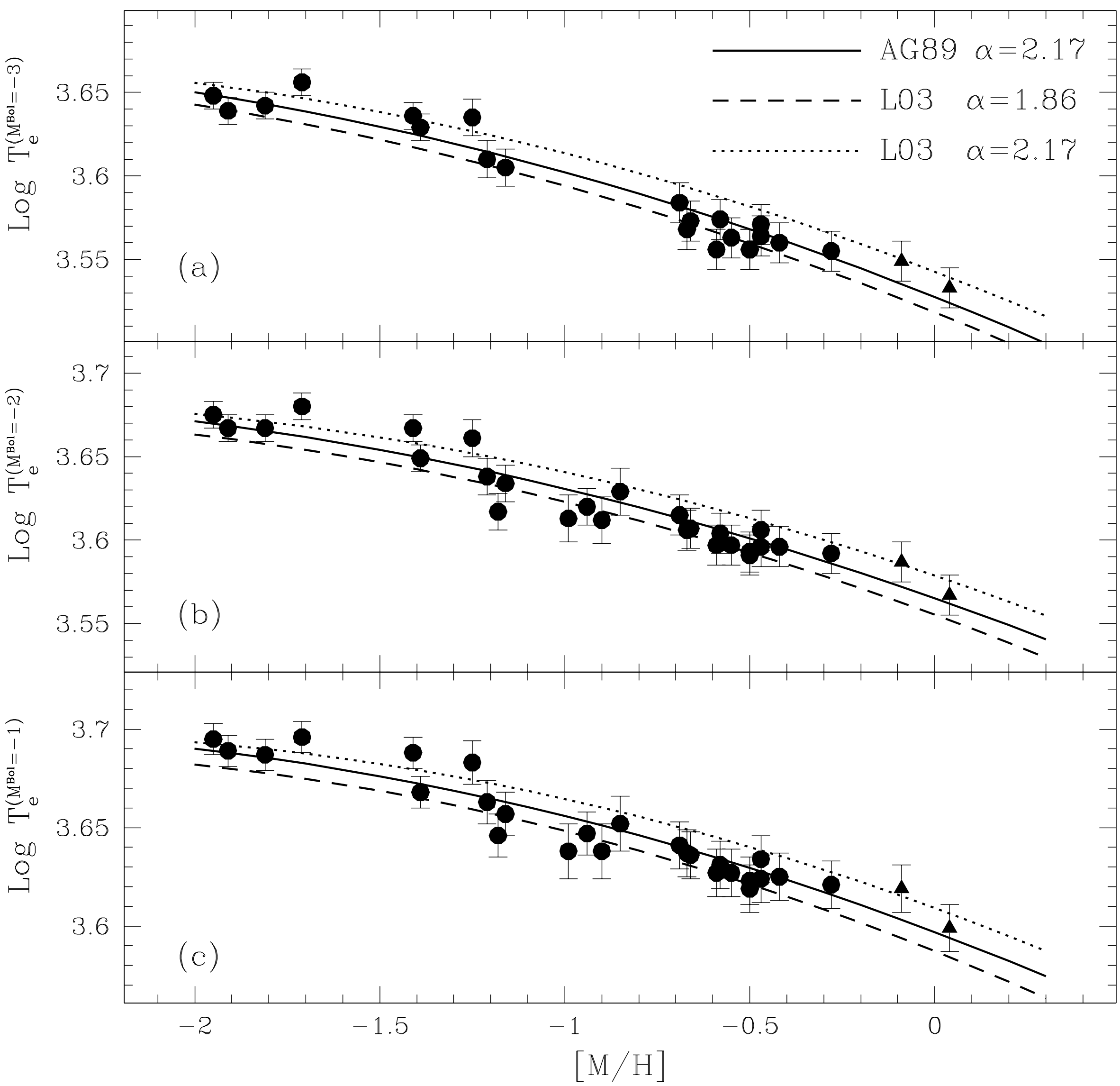

Fig. 3.— As Fig.2 but with overimposed the theoretical predictions: Model prediction with AG89 solar reference and α=2.17 *(solid lines)*. Model prediction with L03 solar reference and α=1.86 *(dashed lines)* and α=2.17 *(dotted lines)*.